Advanced Environmental Carrier Coating Development and Validation for SiC/SiC Ceramic Matrix Composite Turbine Engine Components

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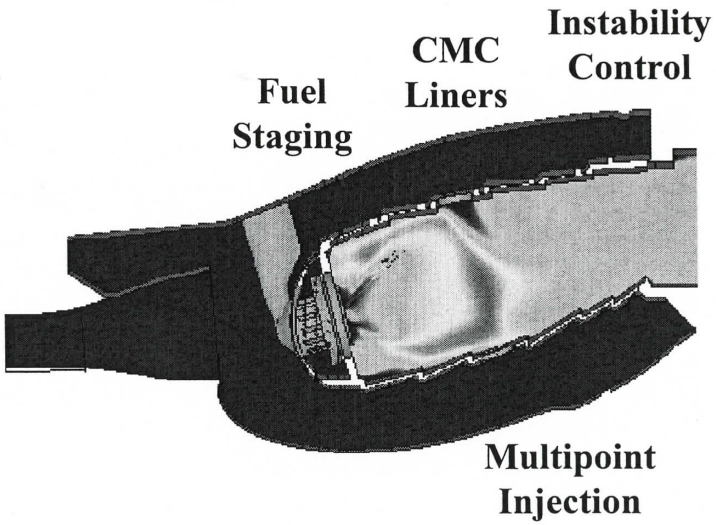
Outline

- **Environmental barrier coating system development: needs and challenges**
- **Advanced environmental barrier coating systems for CMC airfoils and combustors**
  - NASA coating technologies
  - Current turbine and combustor EBC coating emphases
- **Development of next generation environmental barrier coatings**
  - Advanced processing
  - Advanced testing and CMC-EBC rig demonstrations
- **Summary and future directions**

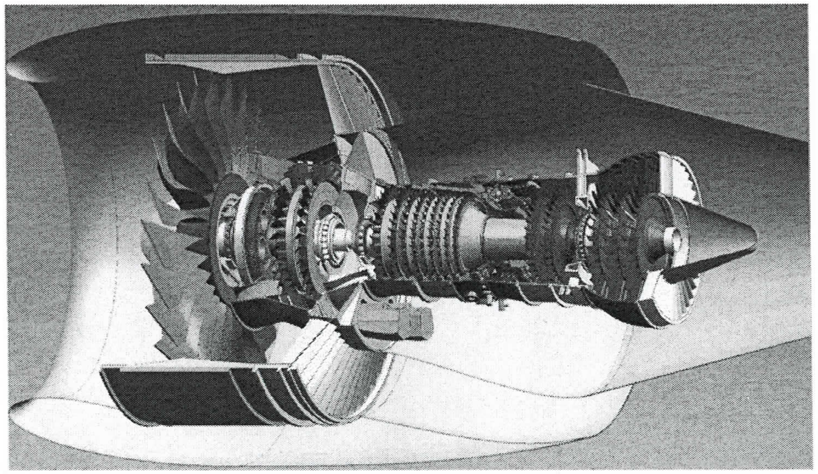
NASA Environmental Barrier Coating (EBC) - Ceramic Matrix Composite (CMC) Program Overview

- **NASA Fundamental Aeronautics Program (FAP)**: Next generation high pressure turbine airfoil environmental barrier coatings with advanced CMCs
  - N+3 generation (2020-2025) with advanced 2700°F CMCs/2700-3000°F EBCs (uncooled/cooled)

- **NASA Environmentally Responsible Aviation (ERA) Program**: Advanced environmental barrier coatings for SiC/SiC CMC combustor and turbine vane components, technology demonstrations in engine tests
  - N+2 generation (2020-2025) with 2400°F CMCs/2700°F EBCs (cooled)



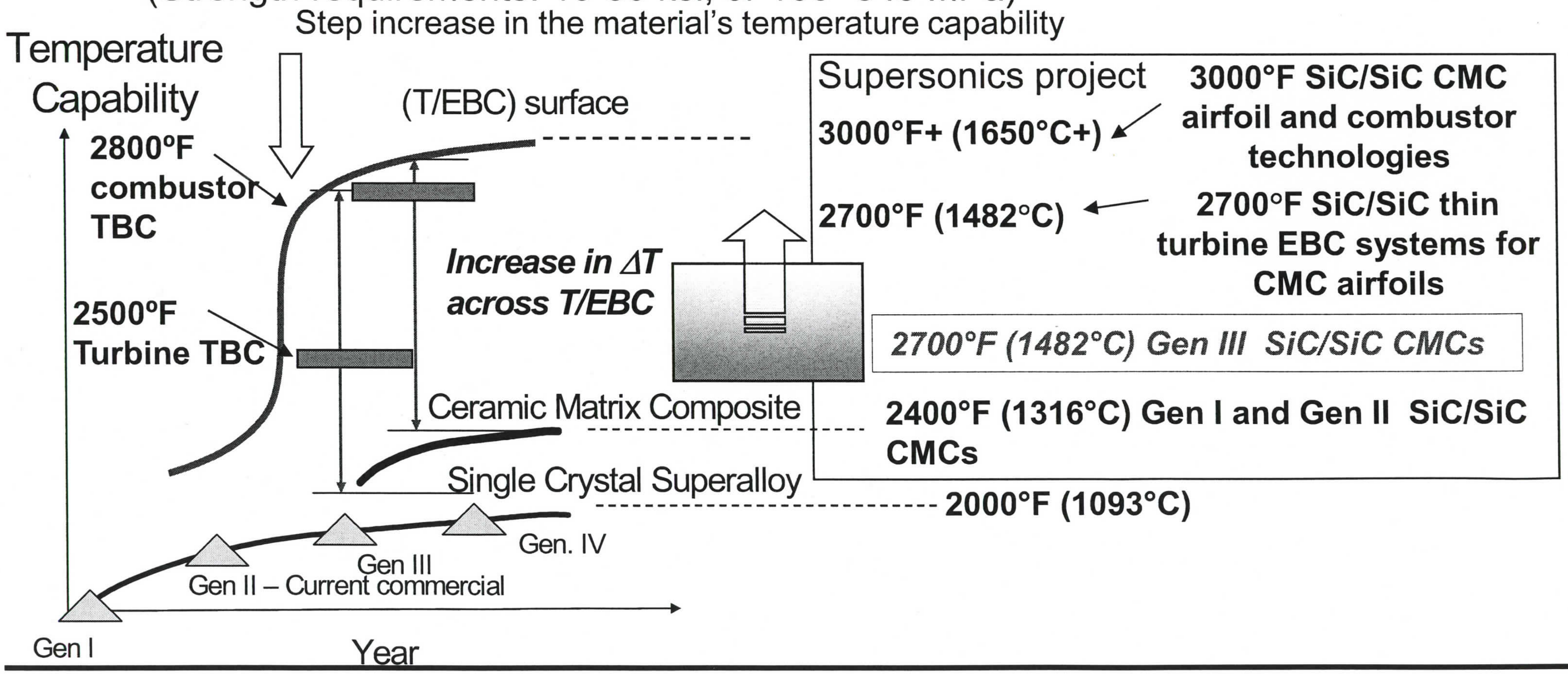
Low emission combustor



High Pressure Turbine CMC vane and blade

NASA EBC and CMC System Development

- Emphasize temperature capability, performance and *long-term* durability
- Develop innovative coating technologies and life prediction approaches
- Meet 9,000 h supersonic engine and 1000 h subsonic engine hot-time life requirements
  - Recession: <5 mg/cm^2 per 1000 h
- Highly loaded EBC-CMCs capable of thermal and mechanical (static/low cycle and dynamic) loading
  - (Strength requirements: 15-50 ksi, or 100- 345 MPa)



CMC-EBC Systems for Turbine Engine Components

	Combustor Liner (medium heat flux)	**HPT Vane** (high heat flux)	**HPT Blade** (very high heat flux)	**LPT Blade** (low heat flux)
Gen II CMC	2400 °F CMC, cooled, 2700 °F **thick** EBC	2400 F CMC, cooled, 2700 °F <u>thin</u> EBC	*2400 °F CMC, cooled, 2400-2700 °F <u>thin</u> EBC*	2400 °F CMC, uncooled, 2400 °F <u>thin</u> EBC
Gen III CMC – Option 1	2700 °F CMC, uncooled, 2700 °F ***thick*** EBC	2700 F CMC, uncooled, 2700 °F <u>thin</u> EBC	2700 °F CMC, uncooled, 2700 °F <u>thin</u> EBC	2400 °F CMC, uncooled, 2400 °F <u>thin</u> EBC
Gen III CMC – Option 2	2700 °F CMC, cooled, 3000 °F **thick** EBC	2700 °F CMC, cooled, 3000 °F <u>thin</u> EBC	2700 °F CMC, cooled, 3000 °F <u>thin</u> EBC	2700 °F CMC, uncooled, 2700 °F <u>thin</u> EBC

Environmental Barrier Coating Developments for Turbine Engine Components - NASA ERA Project

- **The CMC combustor EBC development objectives (TRL 4-5)**

– Develop a 2700-3000°F thin (<15 mil) plasma-sprayed or hybrid-EB-PVD EBC system with 2400°F capable SiC/SiC CMC system with 1000 hr durability goals;

- Designed with high temperature stability and low thermal conductivity coatings for Gen II Prepreg SiC/SiC CMCs
- Develop advanced plasma spray and hybrid plasma - vapor deposition coating systems to meet durability and stability goals
- Develop robust multilayer coating systems including advanced non-Si bond coats through rigorous test matrix evaluations
- Establish EBC-coated CMC specimen and subelement property database incorporating cutting-edge component technologies
  - Film-cooled CMC and CMC-EBC recession and mechanical property database
  - Wear resistant coatings for attachment and integration technologies
- Develop preliminary EBC-coated CMC system life prediction models
- Validate high temperature subelement LCF and HCF performance with attachments
- Demonstrate coated liner systems durability in high pressure high temperature
  - Planned high pressure burner rig test and ASCR test (collaborated with GE)

Environmental Barrier Coating Developments for Turbine Engine Components Under the NASA ERA Project

- **Turbine vane EBCs development objectives (TRL 4-5)**

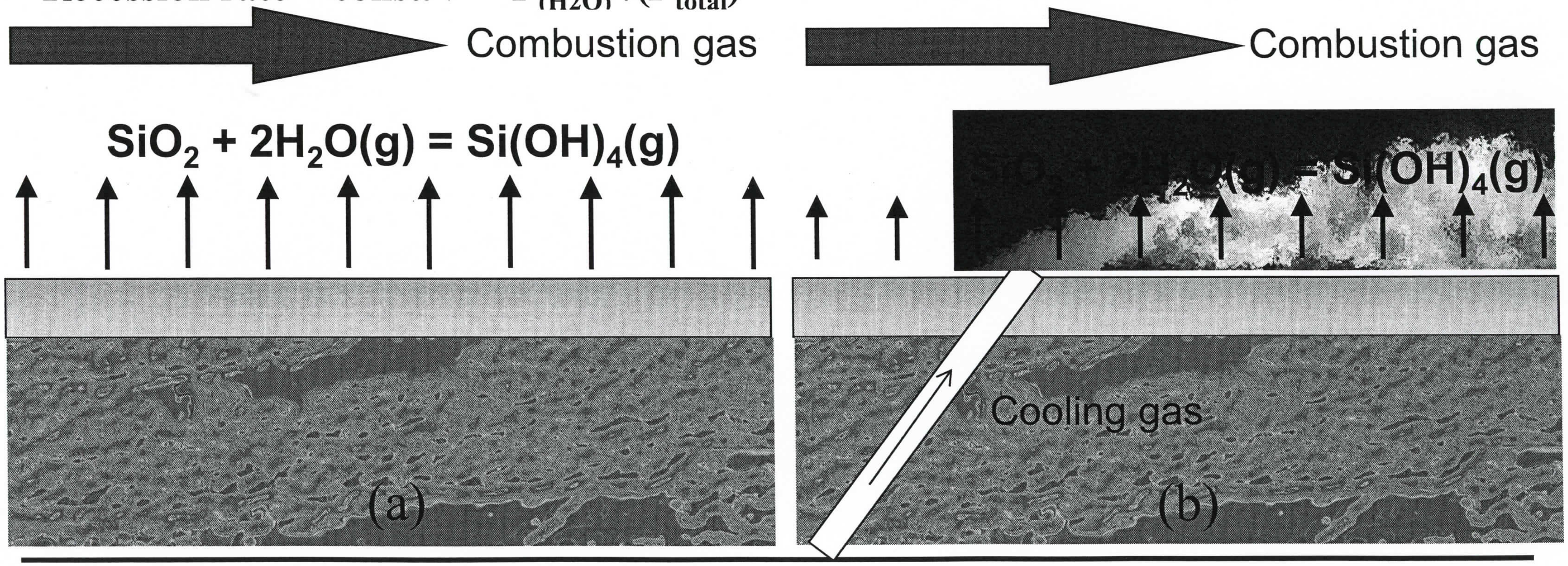
– Develop a 2600-2700°F thin film (5-10 mils in thickness) turbine EBC system combined with advanced, 2400°F capable, high strength SiC/SiC CMC system with 1000 hr durability goals

  - Emphasize high stability coating goals (10 mg/cm^2 specific weight loss, and/or less than 1 mil, 20 micrometer thickness recession in 1000 hours) on Gen II Melt Infiltrated (MI) SiC/SiC and alternative SiC/SiC CMCs
  - Develop thin, multi-component, multilayer turbine coating processing
  - HfO_2-Si composite bond coats, possible future adoption of more advanced bond coats from ERA Combustor and NASA FAP programs
  - Demonstrate high thermal gradient, heat flux, and mechanical loading capabilities of coated systems to meet durability requirements – addressing LE, TE, cooling hole, and substructure (reinforcement rib and endwall) coating/CMC issues
  - Determine high temperature interlaminar strength, thermomechanical LCF, impingement and film cooling design performance of coupons and subelements
  - Establish EBC-CMC airfoil property database and life prediction models
  - Demonstrate CMC turbine vane viability and durability in high pressure

SiC/SiC and Environmental Barrier Coating Recession in Turbine Environments

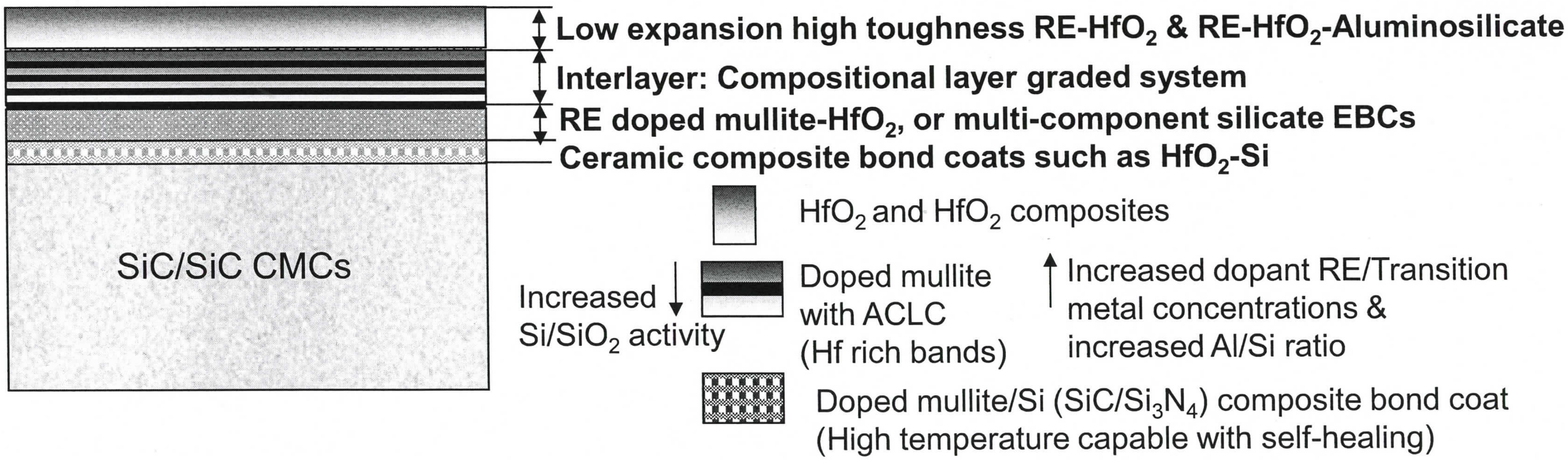
- **Recession of Si-based Ceramics**
  (a) convective; (b) convective with film-cooling
- **Advanced rig testing and modeling** (coupled with 3-D CFD analysis) to understand the recession behavior in High Pressure Burner Rig
  - Work primarily supported under the ERA Combustor and FAP Supersonics projects
  - Also closely collaborate with GE Aviation and GE Global Research

Recession rate = const. $V^{1/2} P_{(H2O)}{}^{2}/(P_{total})^{1/2}$



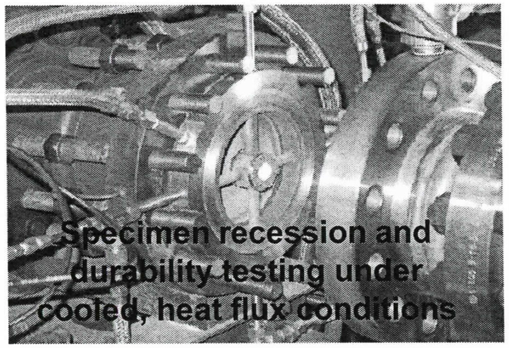
Environmental Barrier Coating Systems for Si-Based Ceramic Matrix Composites

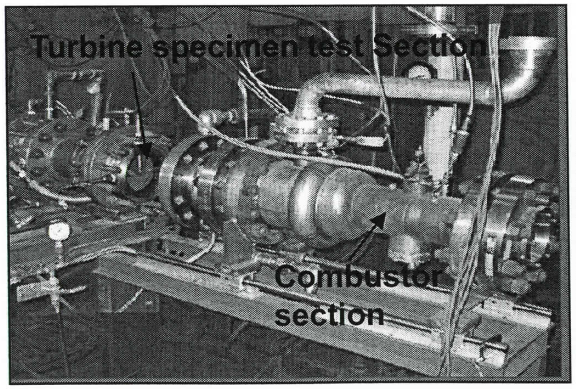
- Advanced multi-component high-stability HfO_2 and/or Hafnium-Rare Earth (RE) based oxide and silicate systems, demonstrated with durability and stability
  - Compositions are being down-selected
- Alternating composition layered/ nano-composite high toughness coating
  - Developed for impact, erosion and cyclic fatigue resistance
- Oxide-Si advanced composite bond coats and alternative non-silicon bond coats
  - The bond coats have demonstrated initial exceptional temperature capability

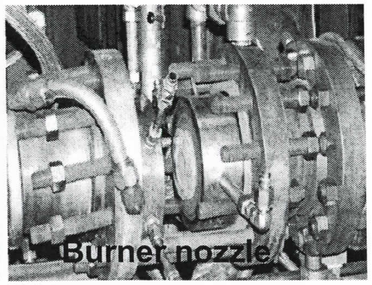


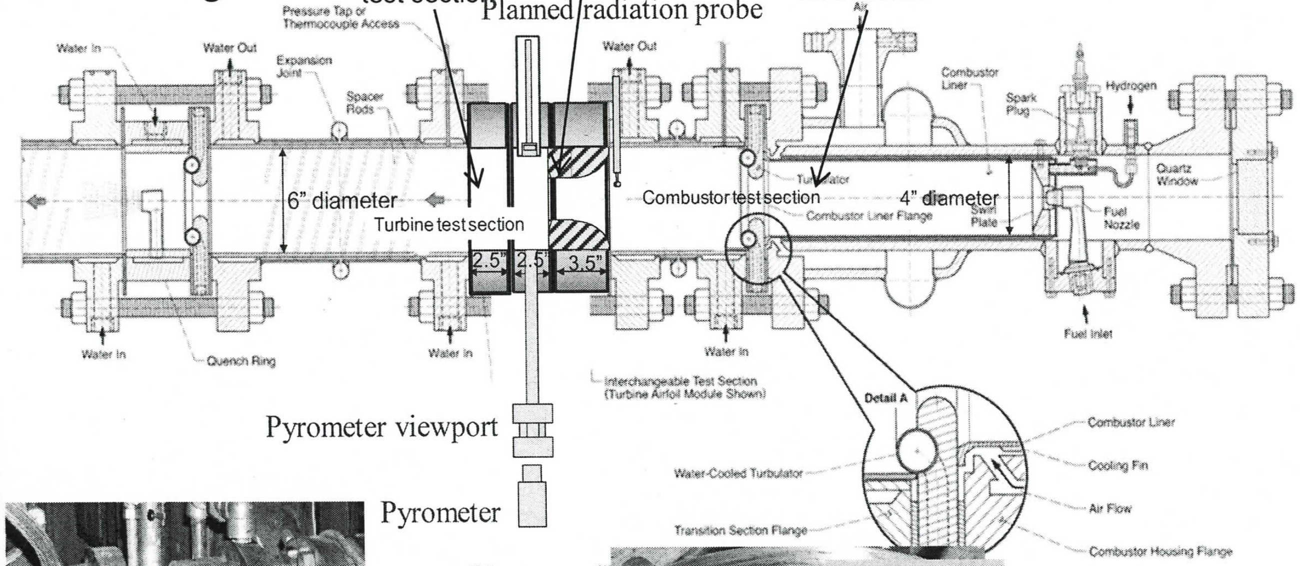
High Velocity and High Pressure Burner Rig Established for Turbine and Combustor CMC-EBC Testing

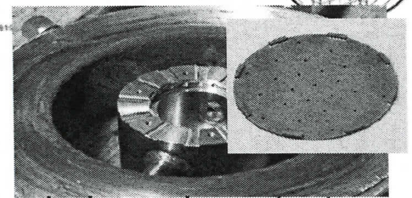
- Jet fuel & air combustion with mass air flow 1.5-2.0 lb/s and gas temperature above 3000°F
- Adjustable testing pressures from 4 to 16 atmospheres, independent controls of sample temperature, testing pressure, and gas velocity
- Cooling air heater system for up to 1200F cooling air
- Up to 850 m/s combustion gas velocity in the turbine testing section
- Cooled, pressurized (600 psi) subelement and subcomponent testing, air impingement cooled combustor segments and liner testing







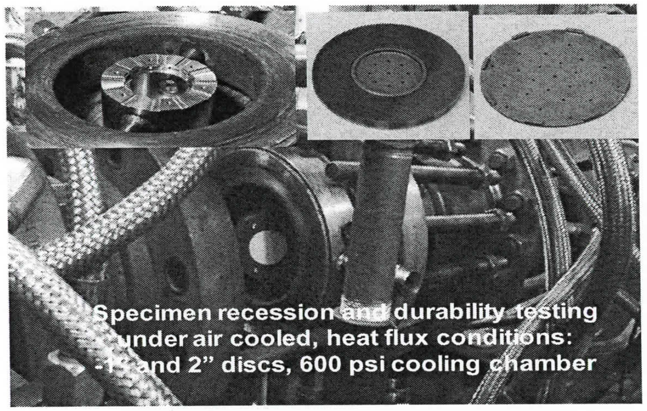


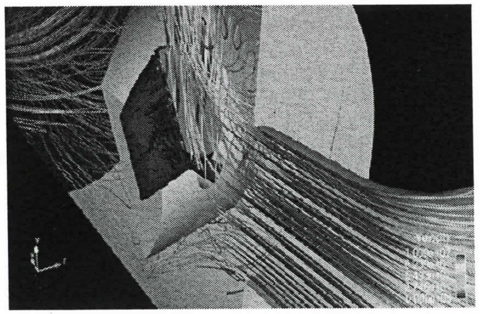


Cooled specimen tests

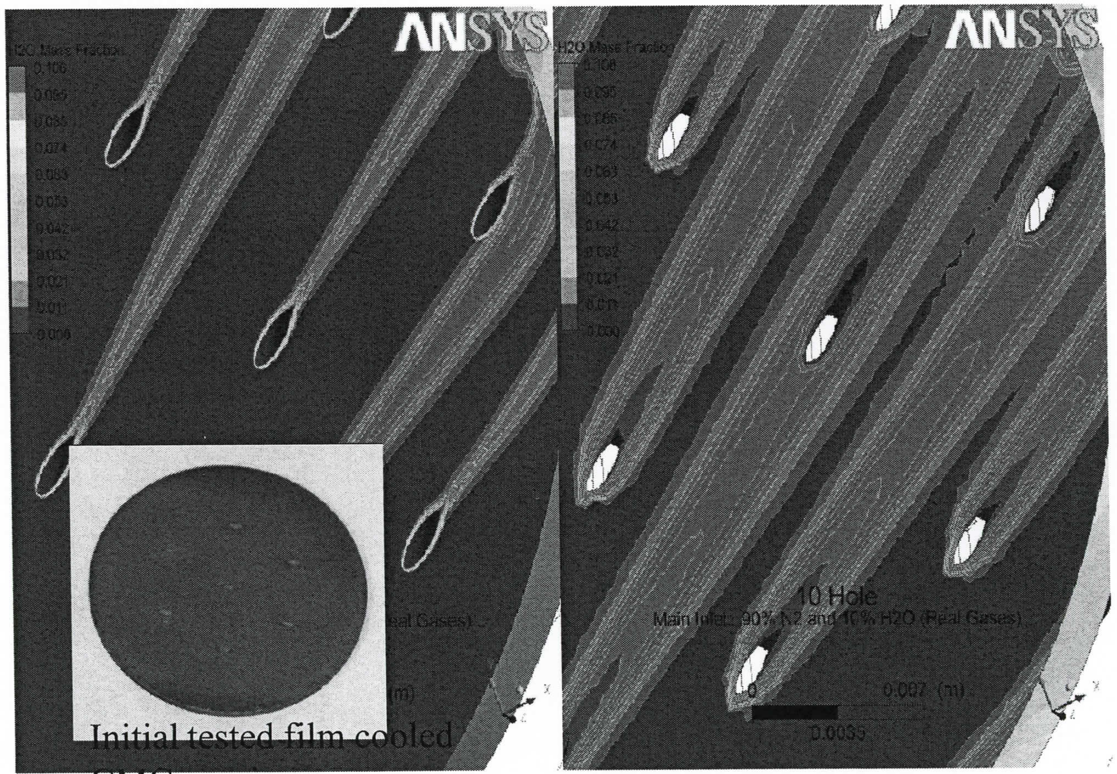
High Pressure High Velocity SiC/SiC Recession Studies - Continued

- Determine recession under very high pressure and high velocity
- Incorporate both impingement and impingement + film cooled test capabilities
- Validate 3D CFD modeling capabilities
- Establish comprehensive recession models





The CFD modeling of film cooled CMC included 10 hole and 17 hole subelements, and water vapor fractions

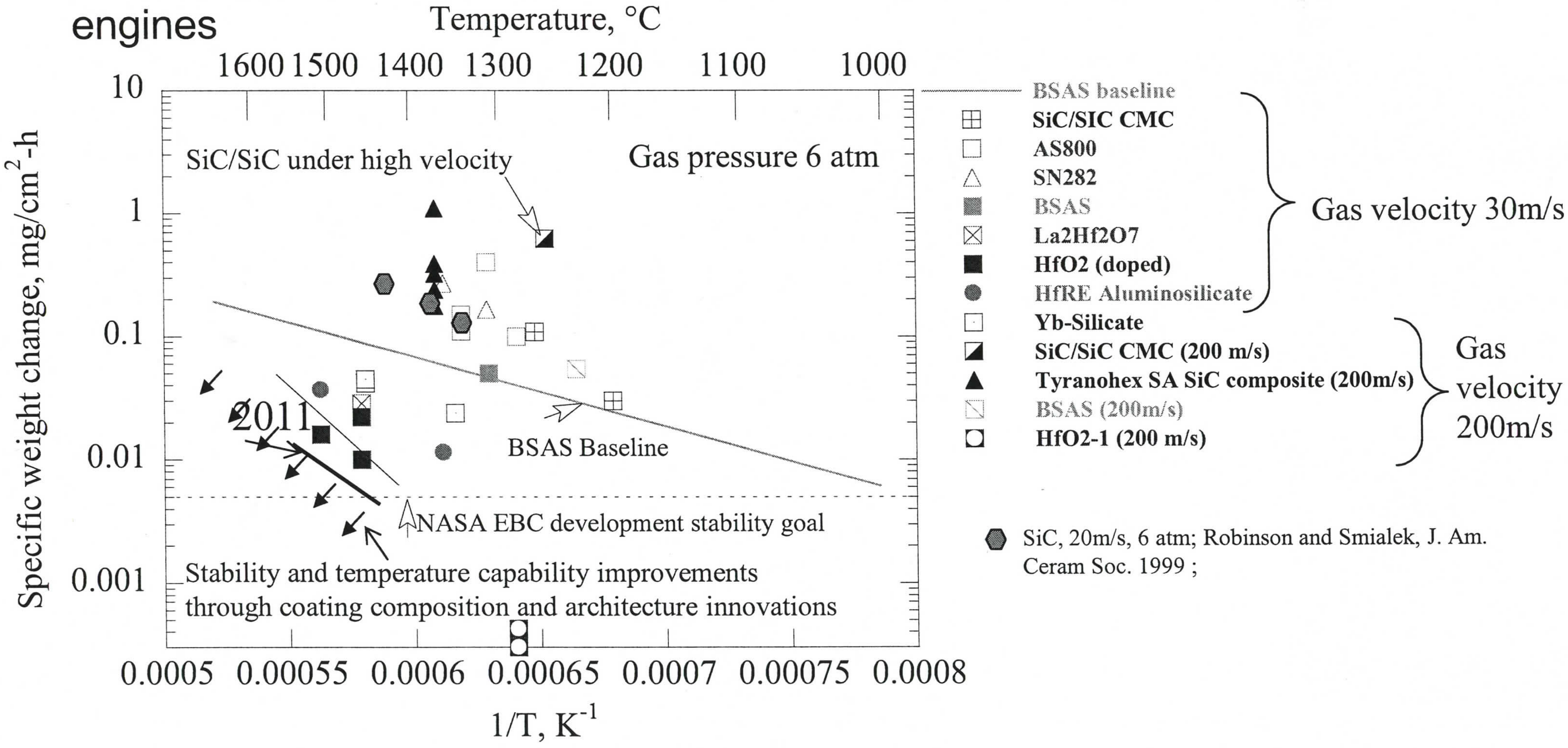


Initial tested film cooled CMC specimen

CFD combustion gas water vapor content

Environmental Stability of Selected Environmental Barrier Coatings Tested in NASA High Pressure Burner Rig

- EBC stability evaluated on SiC/SiC CMCs in high velocity, high pressure burner rig environment
- Stability gaps exist for future high bypass, high operating pressure ratio engines



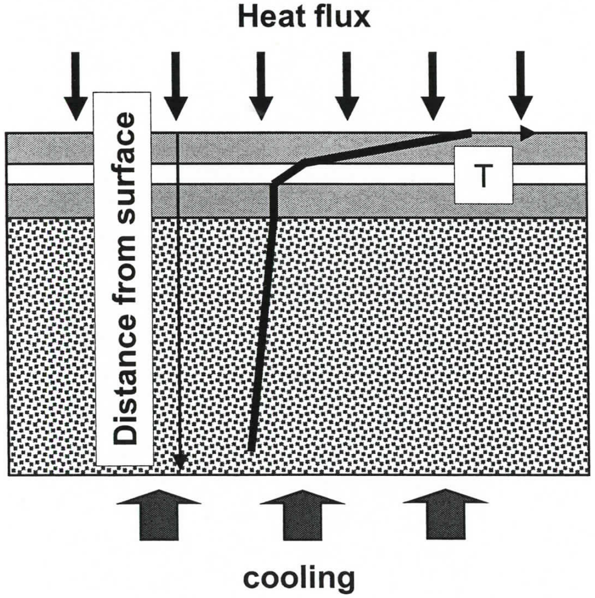
Stability of selected coatings systems

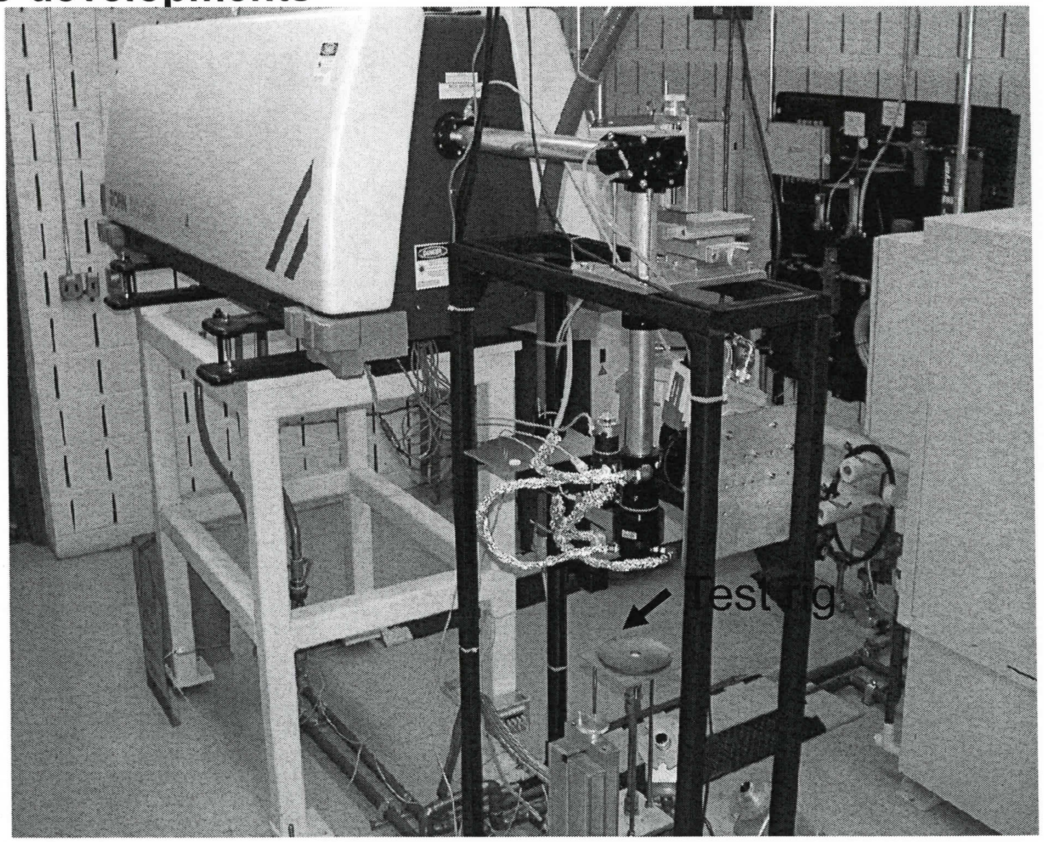
Laser Based High-Heat-Flux Test Approach Adapted for Advanced Turbine and Combustor EBC Development

– **Turbine level high-heat-flux tests crucial for coating developments**

- High power CO_2 laser high-heat-flux rig (315 W/cm^2: easier to achieve for EBC-CMCs)
- Water vapor or steam testing capability
- Capable of subelement and small subcomponents
- Capable thermal conductivity measurements and real time health monitoring
- Crucial for 3000°F (1650°C) EBC-CMC developments

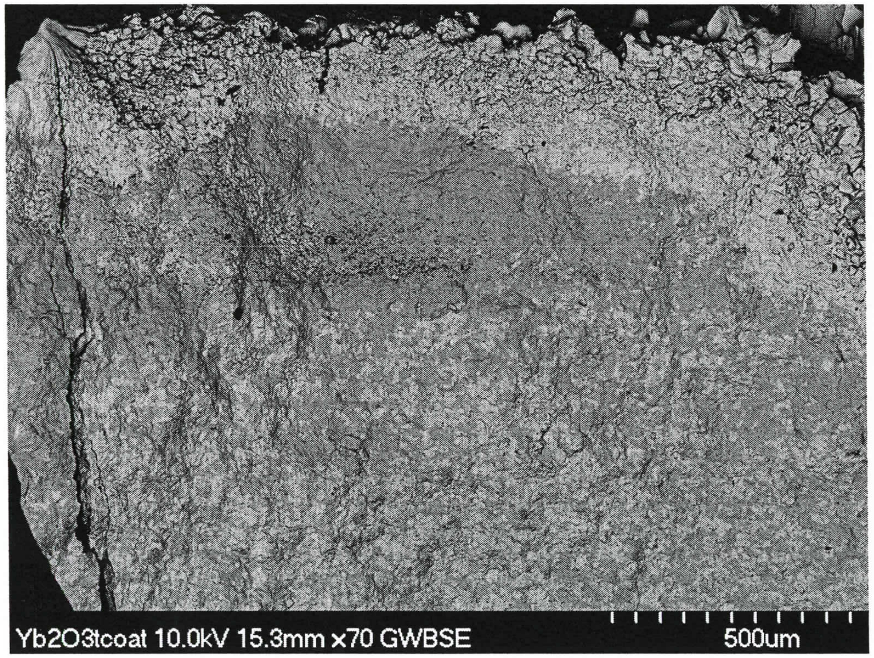
Turbine: 250°F across 100 microns
Combustor: 166°F across 100 microns



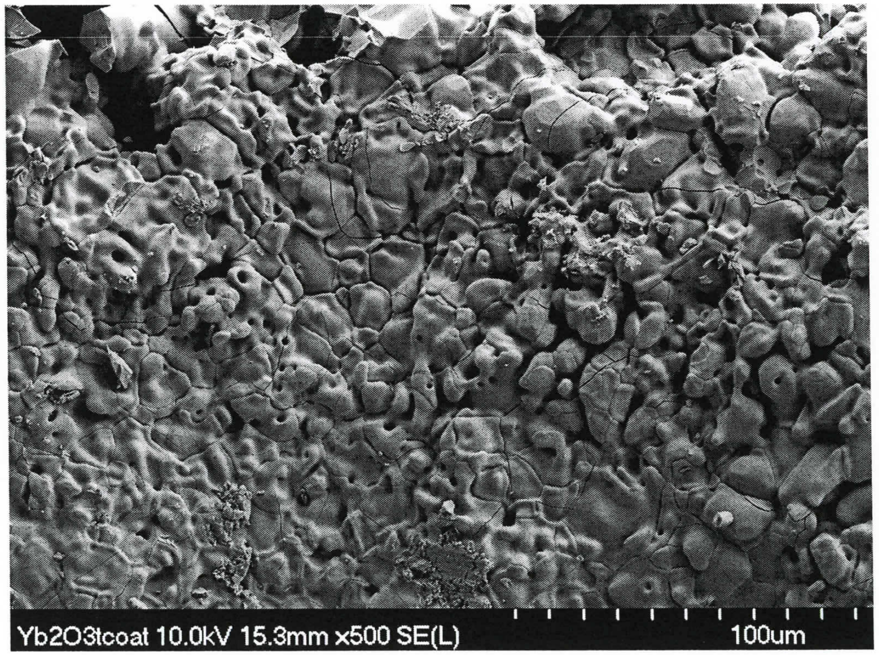


Examples of Recession of Yb_2O_3/Yb_2SiO_5/$Yb_2Si_2O_7$ based Systems

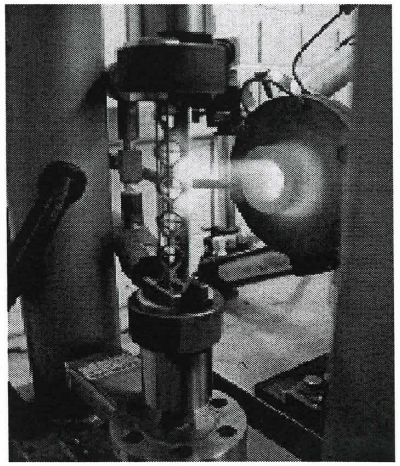
- Tested in laser steam rig at surface temperature of 1400°C and 100% steam
- Non-stable Yb_2O_3 and also quick inter-diffusion between Yb_2O_3 /$Yb_2Si_2O_7$
- Recession of the oxide silicate systems



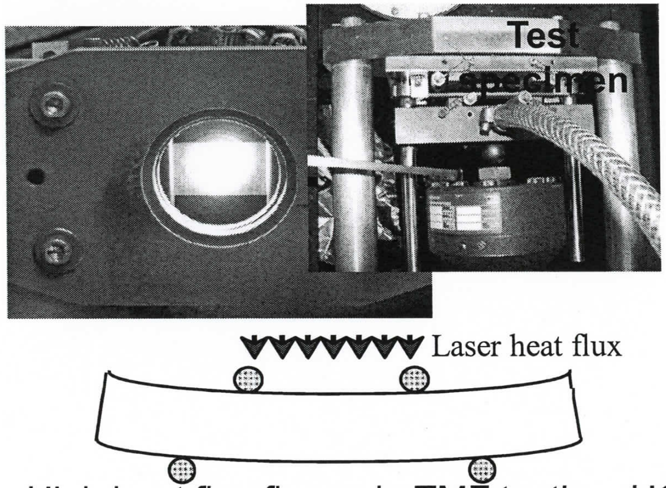
Recession in the top very silica lean region



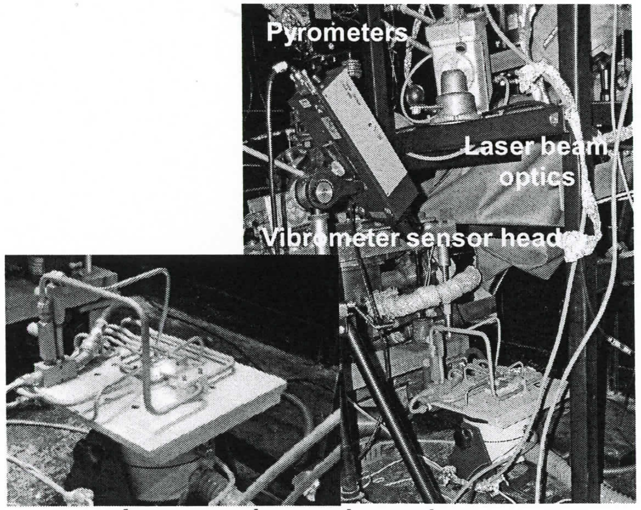
NASA Laser Heat Flux and Burner Rig Testing in Various Simulated Engine Environments



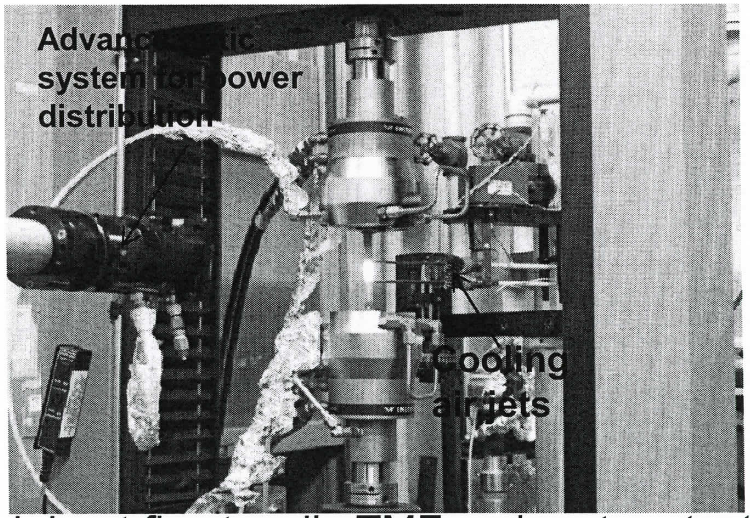
Burner rig rupture, erosion/impact testing



High heat flux flexural –TMF testing: HCF, LCF, Interlaminar and biaxial strengths



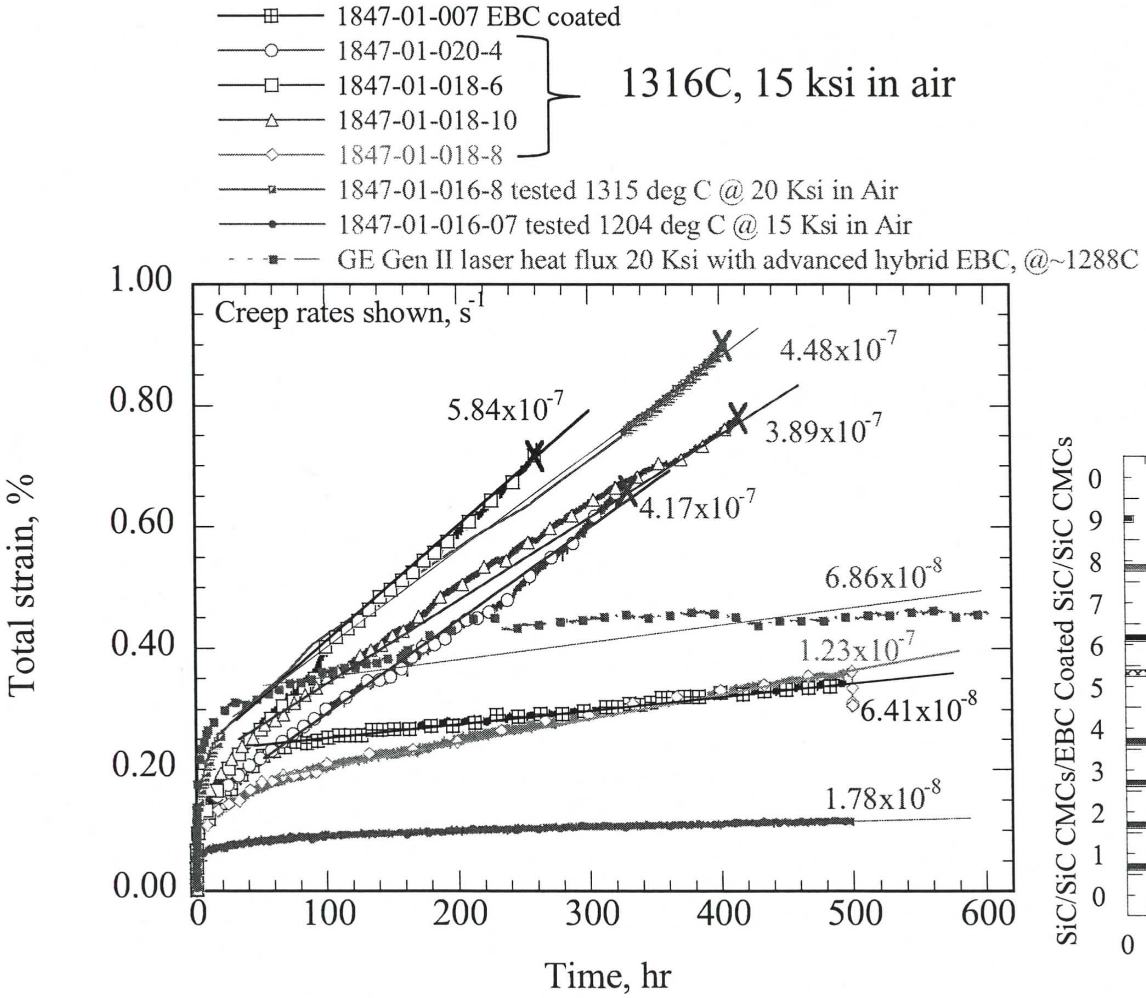
Laser damping rig

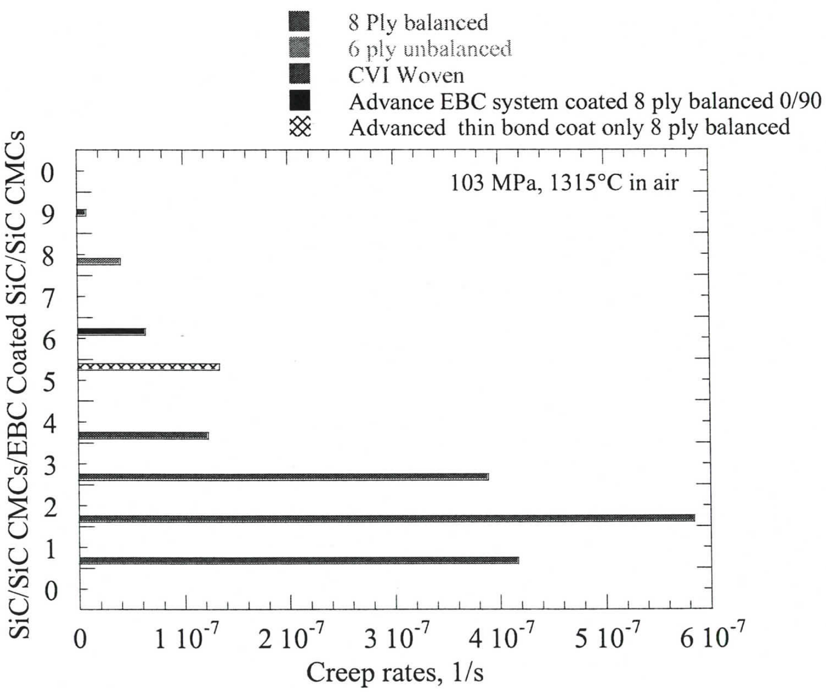


High heat flux tensile TMF and rupture testing

Creep Behavior of Coated and Uncoated Prepreg Gen II CMCs

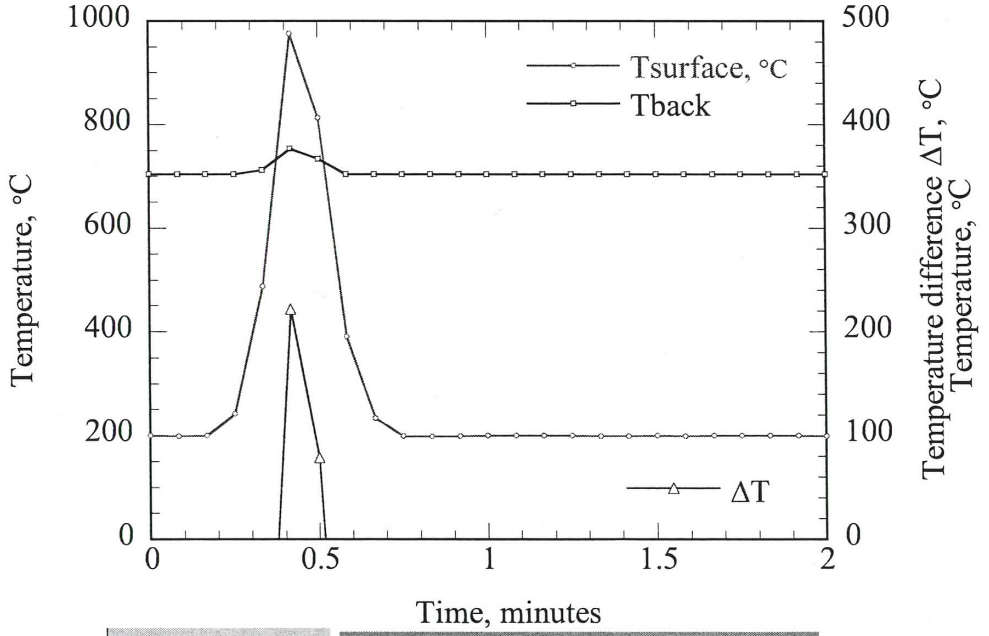
– **Advanced EBC coated specimens tested to determine coating durability and potential environmental effects on CMC creep rupture**

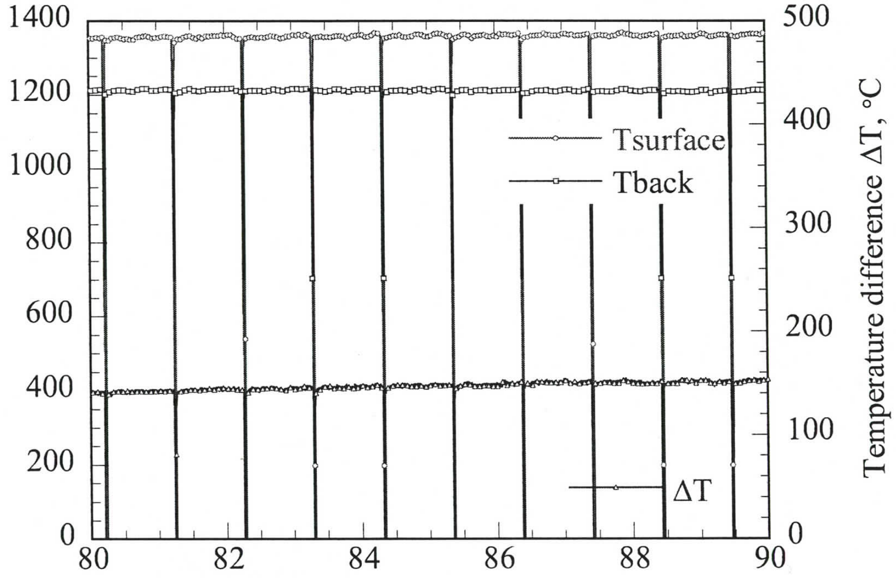


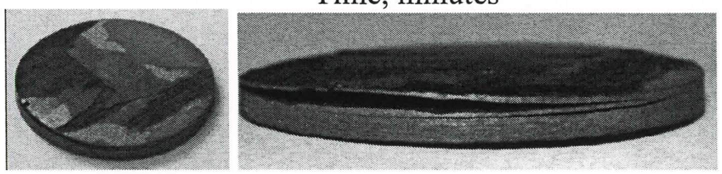


Gen II Prepreg MI SiC/SiC CMC – Initial Thermal Gradient Tests

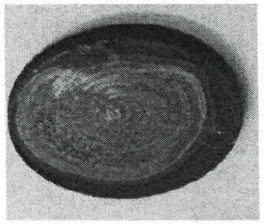
- A first specimen delamination and spalling upon heating during initial thermal transient (approximate heat flux 150 W/cm^2, heat flux, maximum ΔT across the specimen thickness >220°C or about 400°F)
- A second specimen cyclically tested at Tsurface 1320°C (2400°F) and Tback surface 1210°C (2210°F) for 100, 1 hr cycles







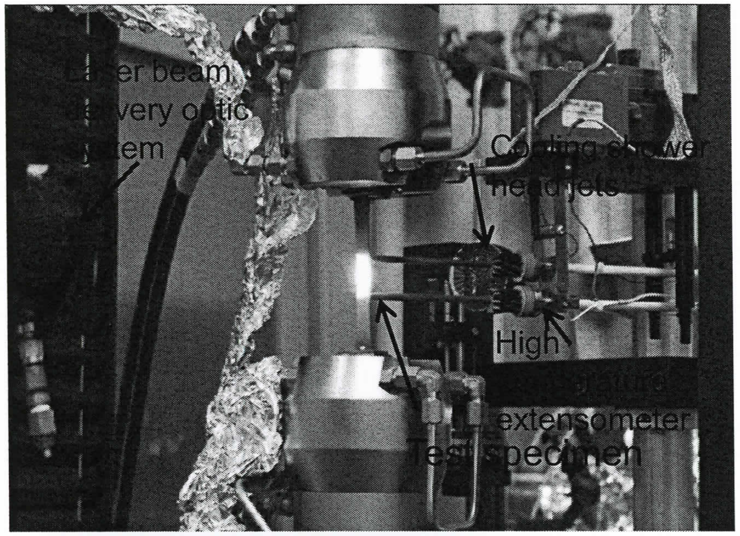
Delaminated and spalled specimens under heat flux



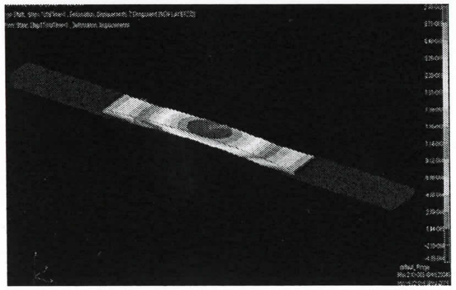
Cyclic tested specimen

Thermal Gradient Tensile Creep Rupture Testing of Advanced Environmental Barrier Coating SiC/SiC CMCs

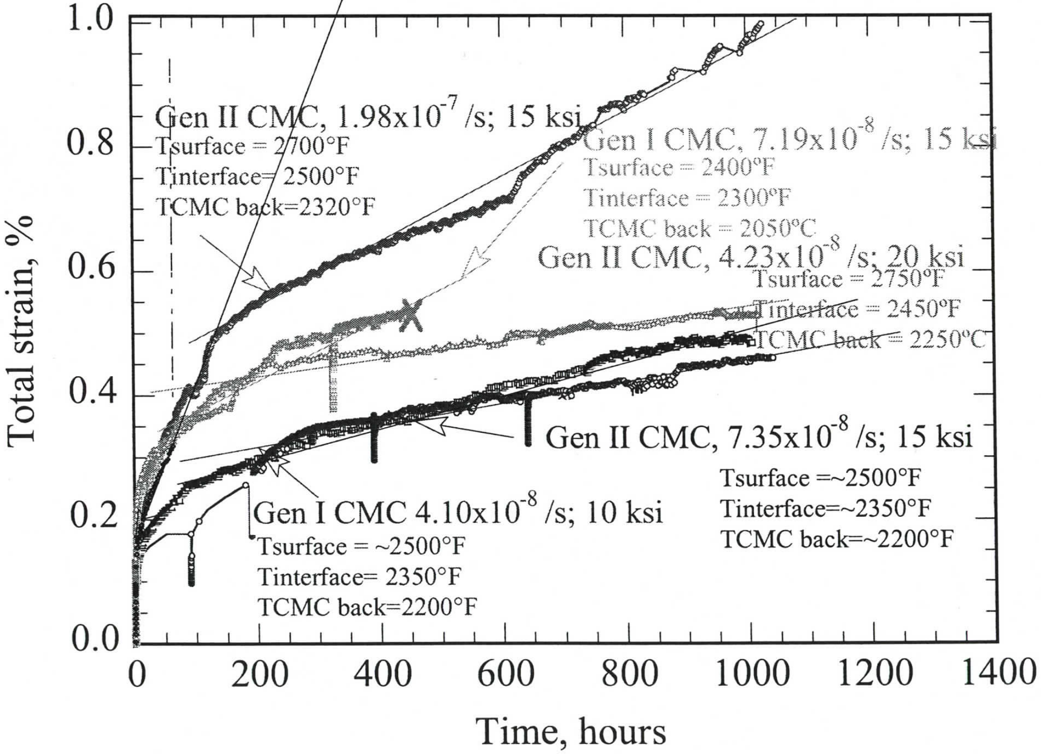
- Advanced high stability multi-component hafnia-rare earth-silicate based turbine environmental barrier coatings being successfully tested for 1000 hr creep rupture
- EBC/CMC high heat flux creep rupture modeling and validation



EBC coated tensile specimen

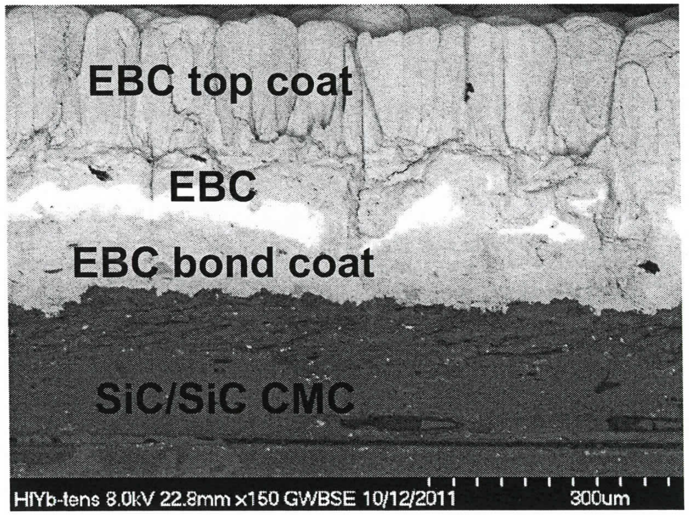


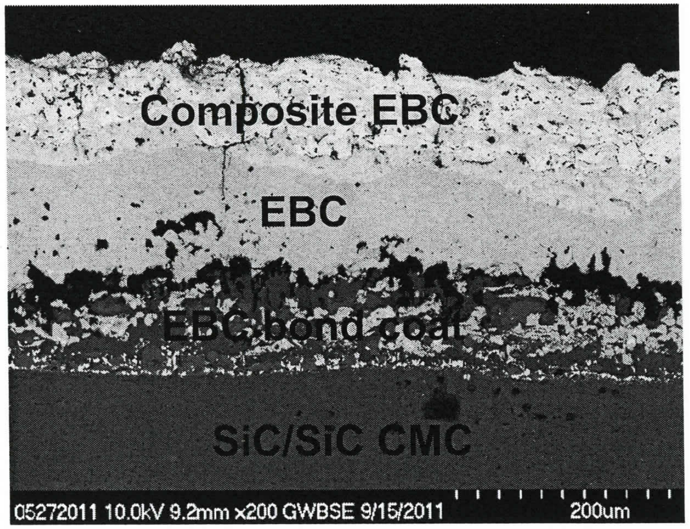
Modeling of Heat-Flux Tensile Creep testing completed



Thermal Gradient Tensile Creep Rupture Testing of Advanced Environmental Barrier Coating SiC/SiC CMCs - continued

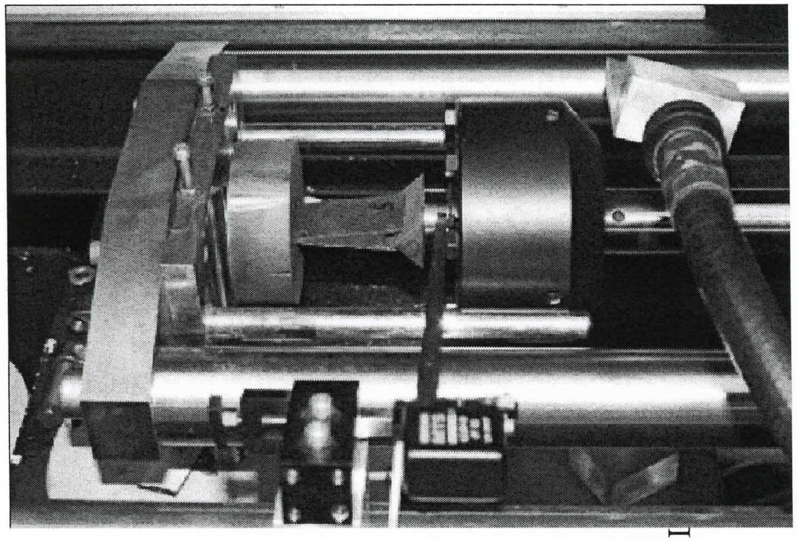
- Coating microstructures after 1000 hr, 1482°C (2700°F), 103 MPa (15 ksi) testing

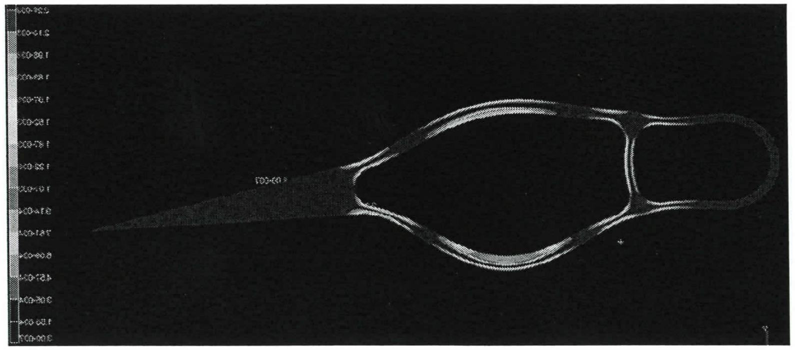


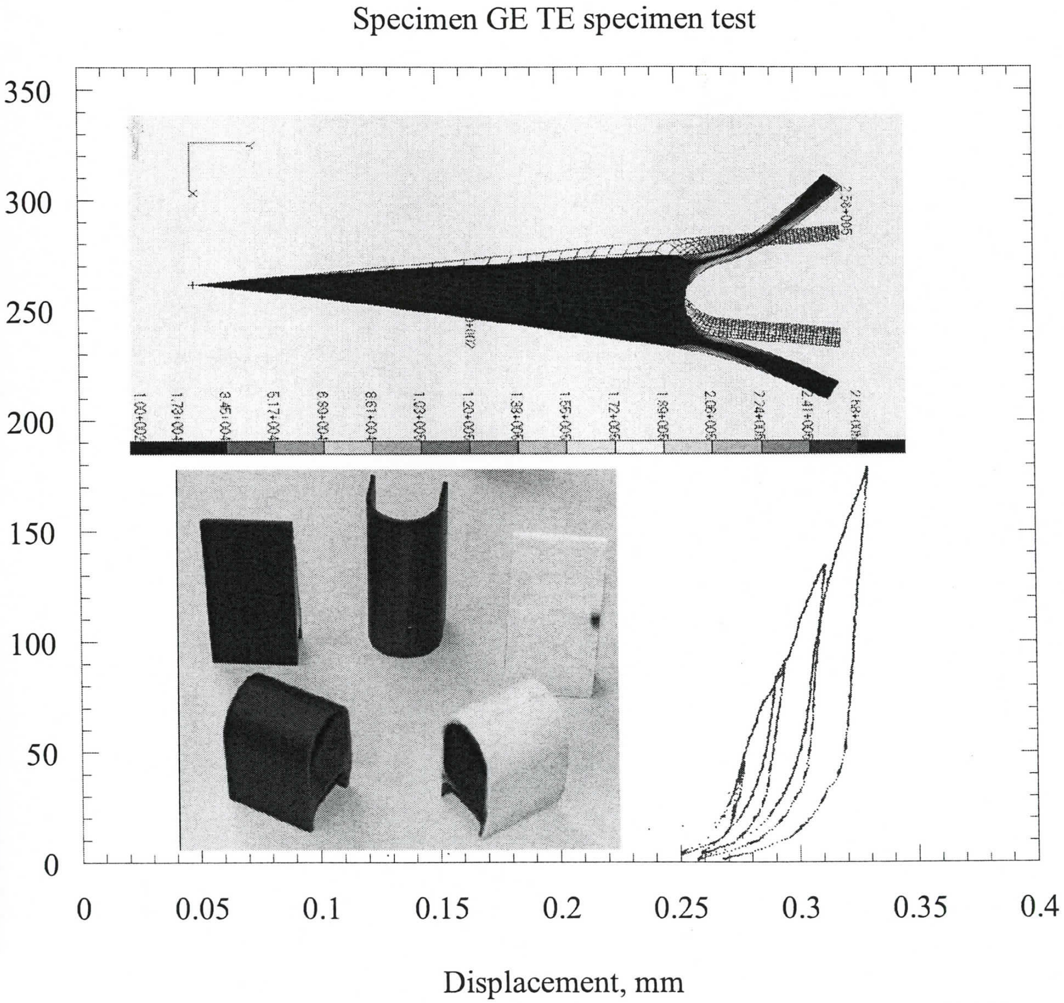


NASA Laser Heat Flux and Mechanical Testing of EBC-Subelements

- **Subelement testing to simulate turbine vane loading**

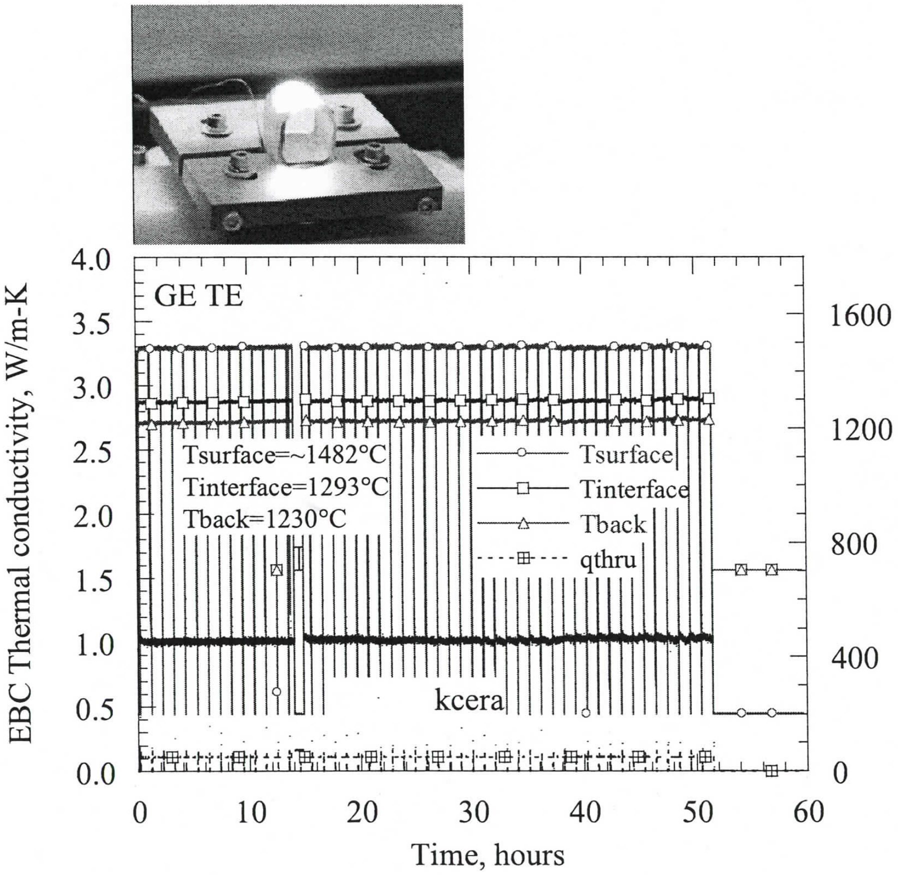


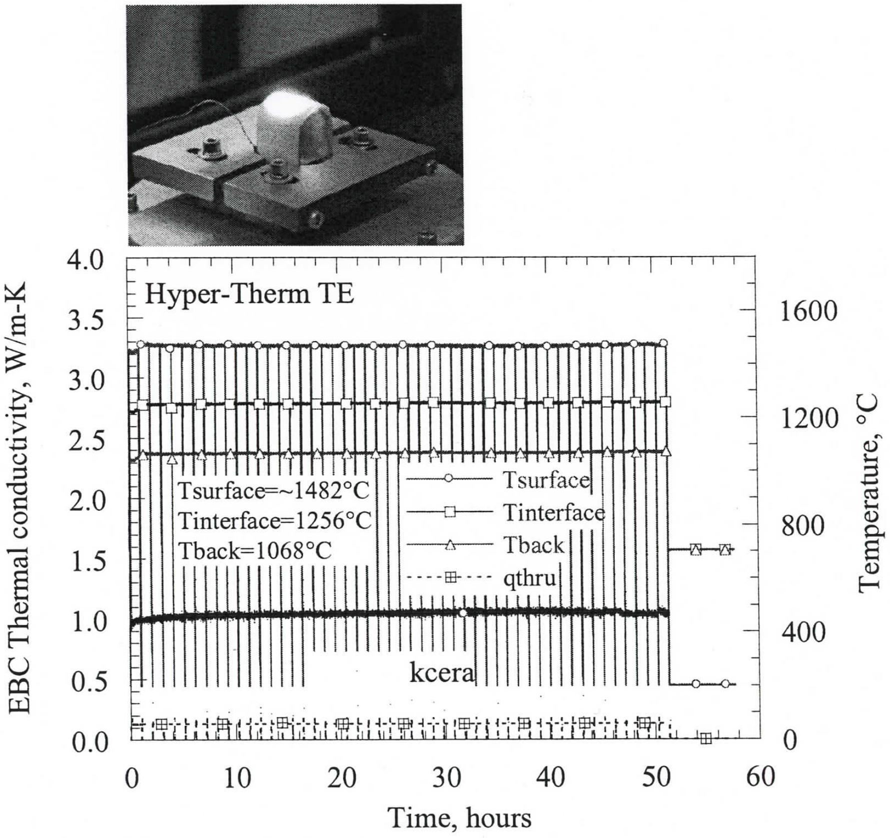




NASA Laser Heat Flux and Mechanical Testing of EBC-CMC Subelements

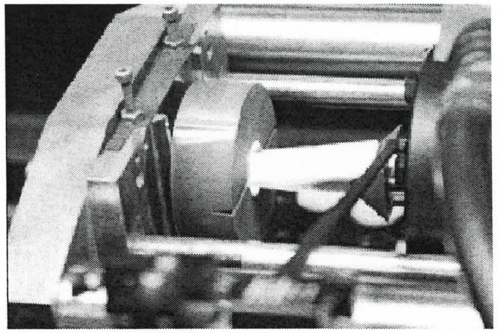
- **Subelements successfully tested for 50, 1 hr hot cycles**

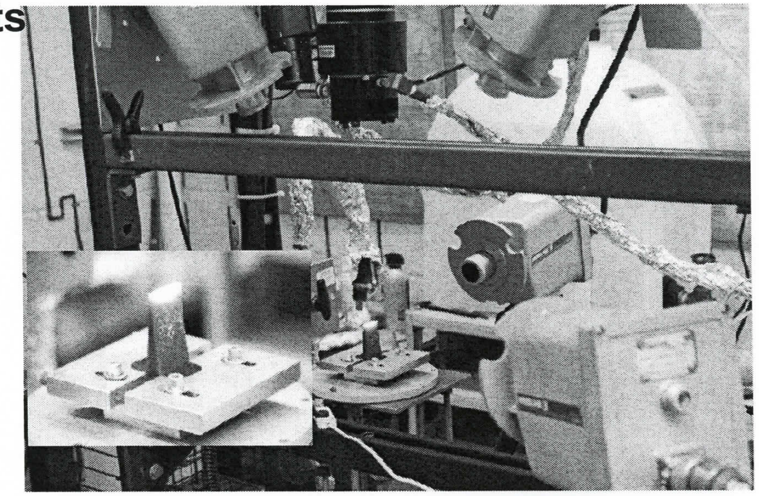


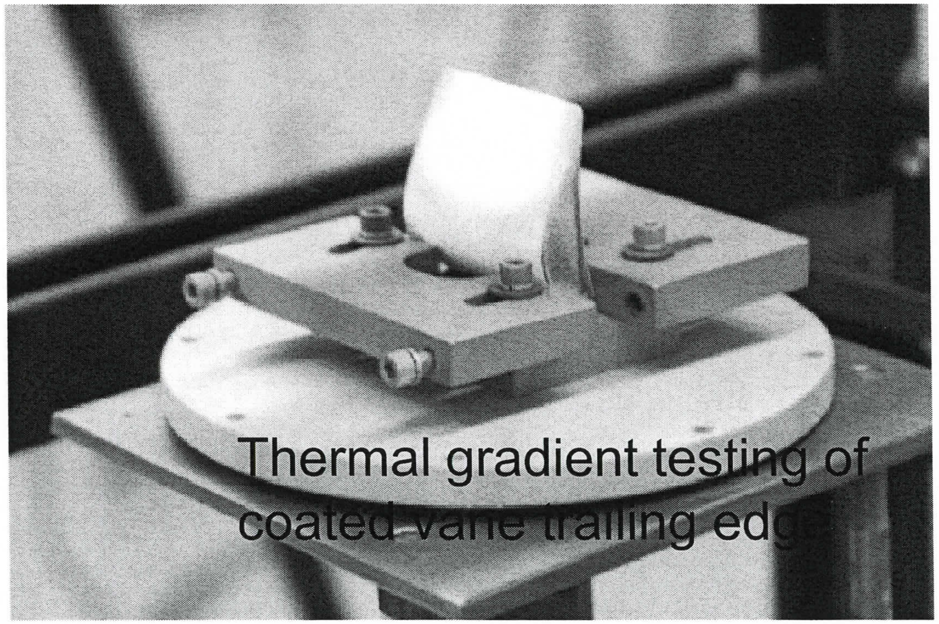


NASA Laser Heat Flux Rig Testing in Various Simulated Engine Thermal Gradients

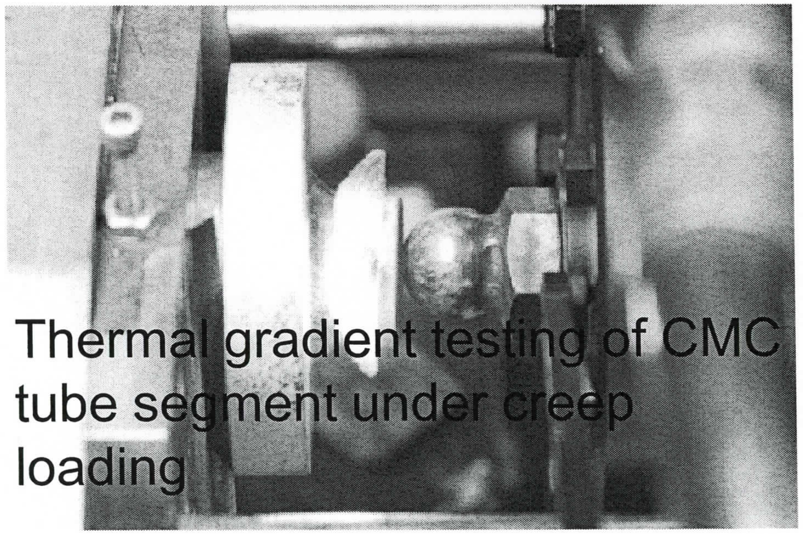
- Subelement tests to simulated thermal gradients







Thermal gradient testing of coated vane trailing edge

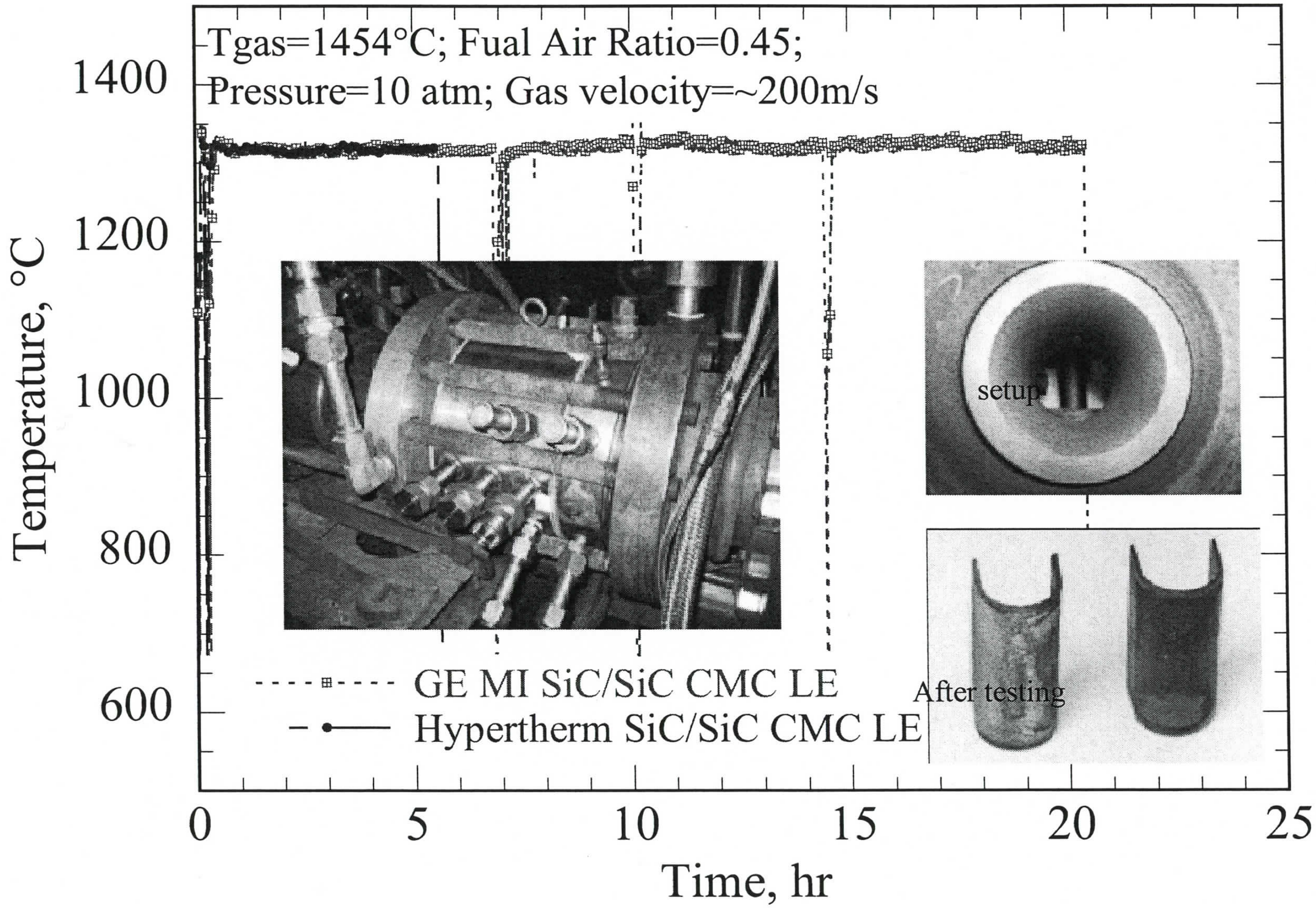


Thermal gradient testing of CMC tube segment under creep loading

High heat flux testing CMC Vane and tube Segments (2700°F)

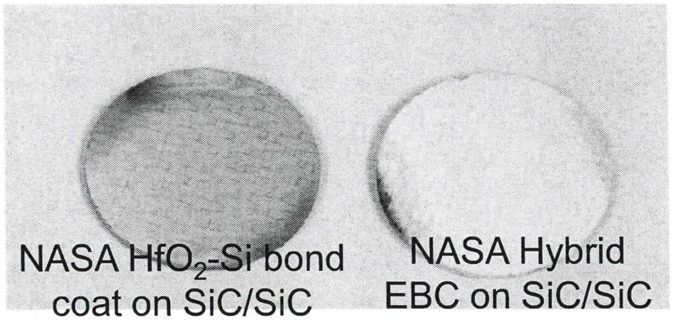
High pressure Burner Rig Testing of CMC Subelements

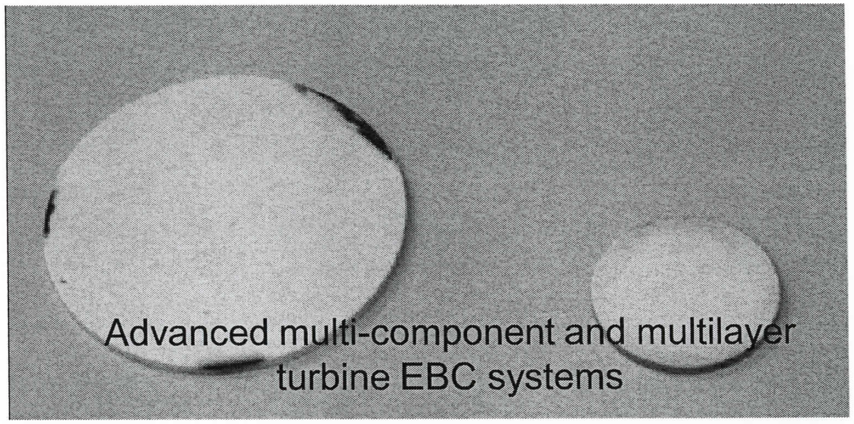
- The tests also coupled with recession tests

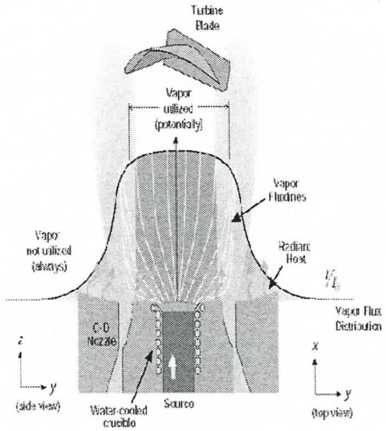


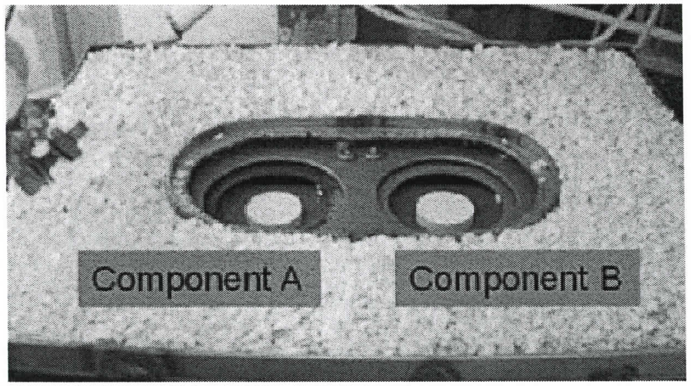
Development of Directed Vapor and Conventional Electron Beam - Physical Vapor Deposition for CMC Combustor and Airfoil Environmental Barrier Coating Processing

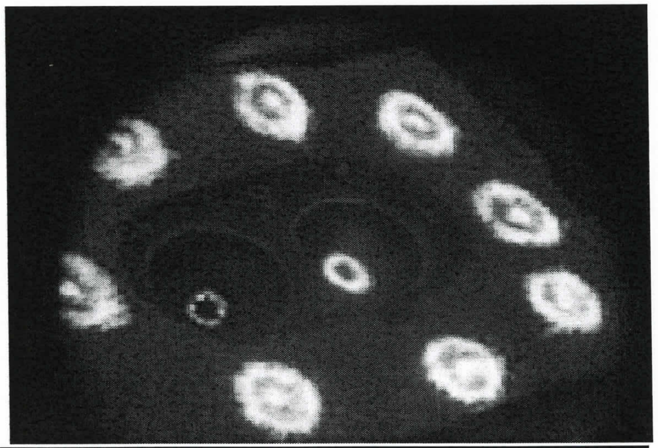
- In collaboration with Directed Vapor Technologies, developing next generation NASA turbine environmental barrier coatings
- Advanced coatings processed for higher TRL ERA combustor and turbine component EBCs (TRL 4-5)


NASA HfO_2-Si bond coat on SiC/SiC NASA Hybrid EBC on SiC/SiC


Advanced multi-component and multilayer turbine EBC systems



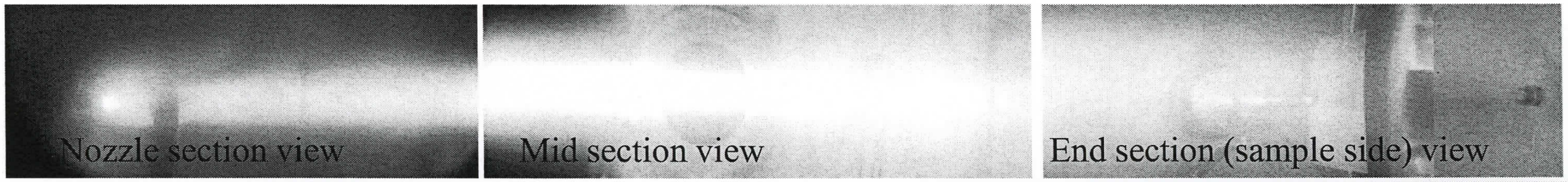


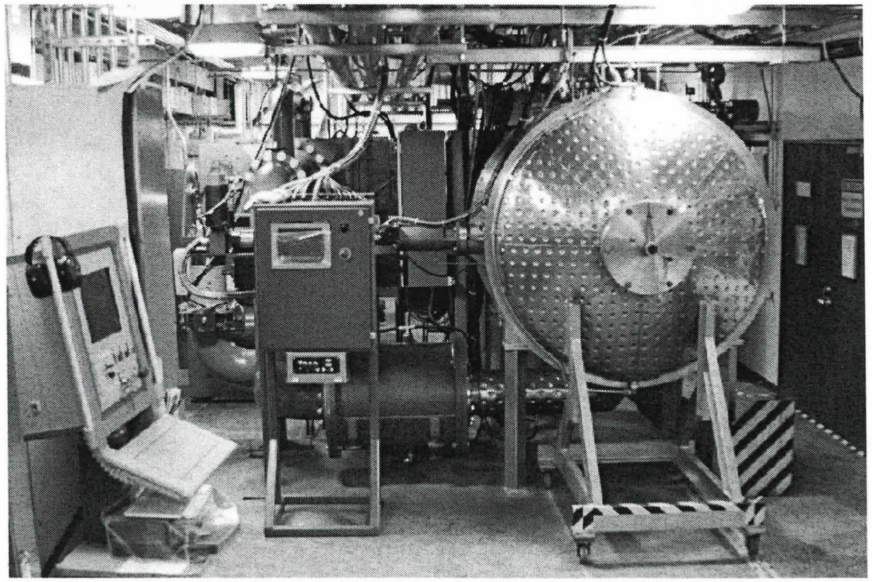


Directed Vapor Processing Systems

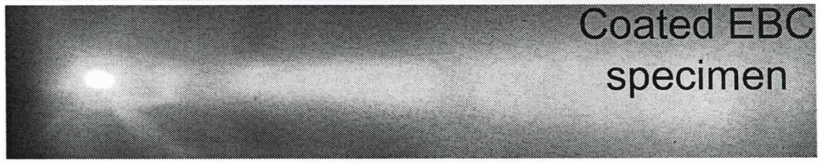
The Development of Plasma Spray - Physical Vapor Deposition (PS-PVD) for CMC Airfoil Coating Processing

– Established under NASA FAP Supersonics Project, advanced Low Pressure PS-PVD coating technology is being developed for next-generation SiC/SiC CMC turbine airfoil coating processing
  - High flexibility coating processing – PVD, CVD and/or plasma-splat coating processing
  - High velocity vapor non line-of-sight coating processing for complex-shape components

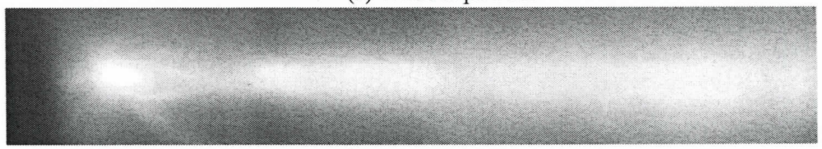




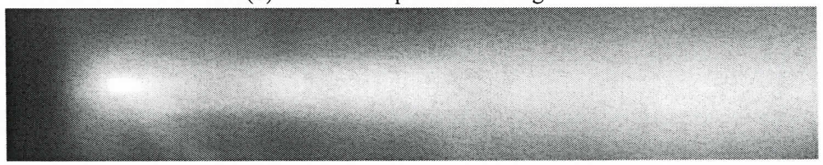
NASA Hybrid PS-PVD coater system



(a) Without powder



(b) With initial powder feeding

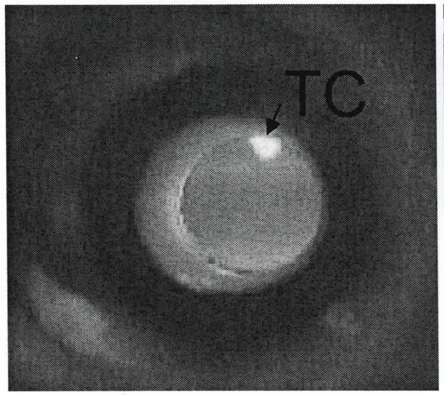


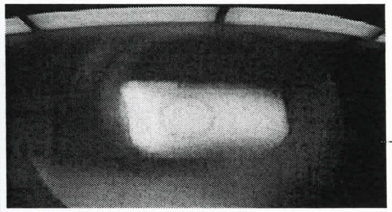
(b) Full powder feeding

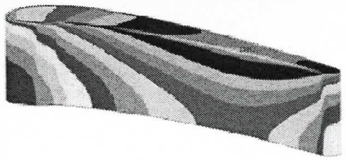
High enthalpy plasma vapor stream for efficient and complex thin film coating processing

High Pressure Burner Rig Demonstrations Planned for Validating EBC Coating and SiC/SiC Components (Gen II SiC/SiC CMC Subcomponents with EBCs)

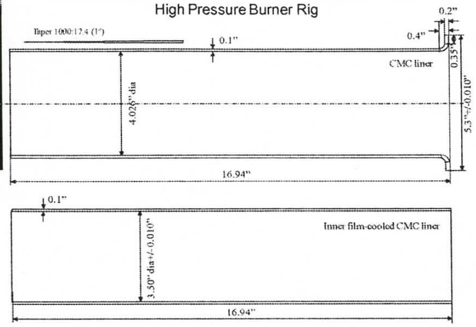
– Improve technology readiness and develop physics-based life prediction models



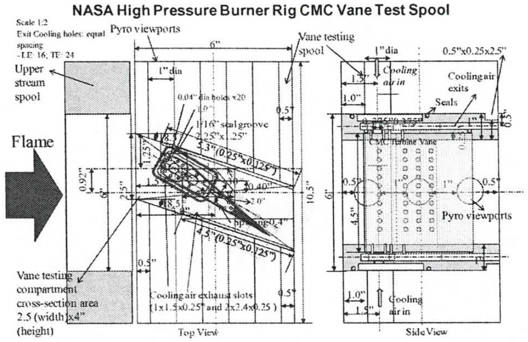




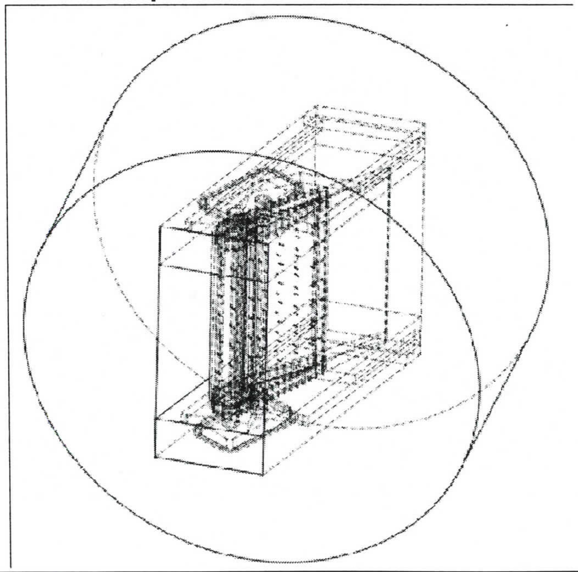
ERA SiC/SiC CMC Combustor Liner Test Articles – NASA High Pressure Burner Rig

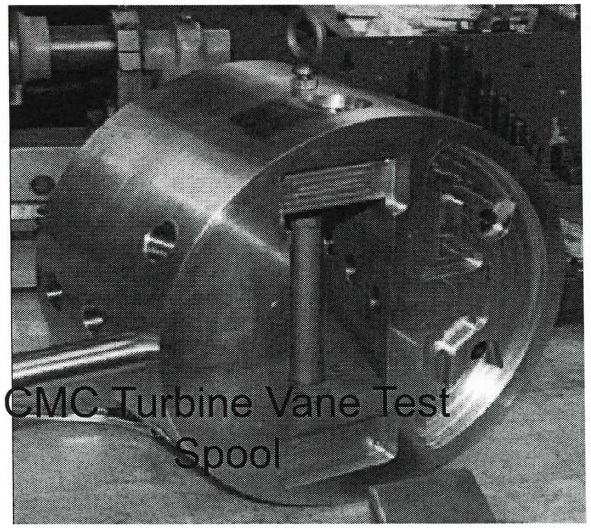


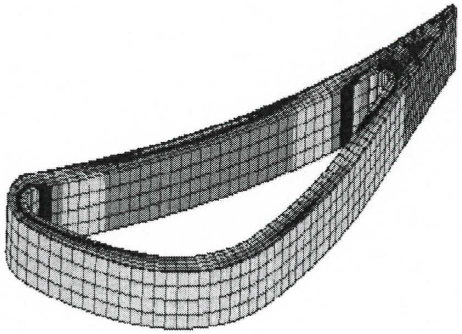
NASA High Pressure Burner Rig CMC Vane Test Spool



Subcomponent and EBC demos and Modeling based on simulated engine subelement and subcomponent tests



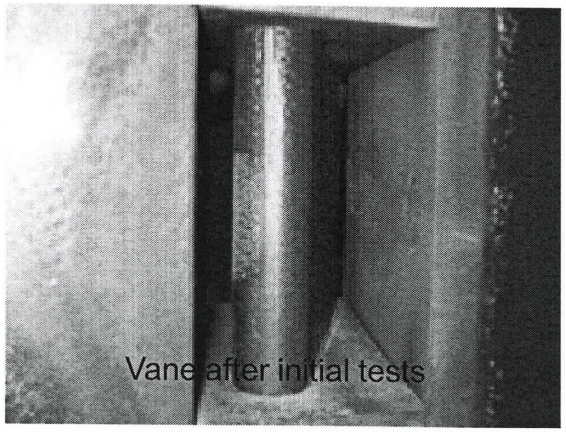


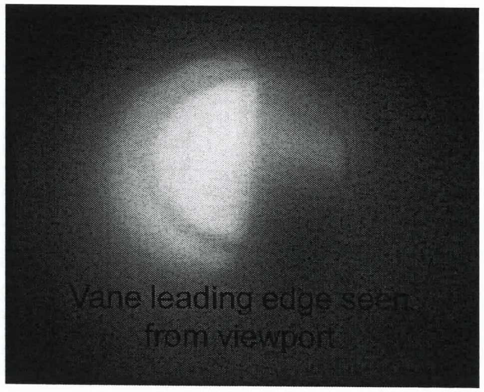


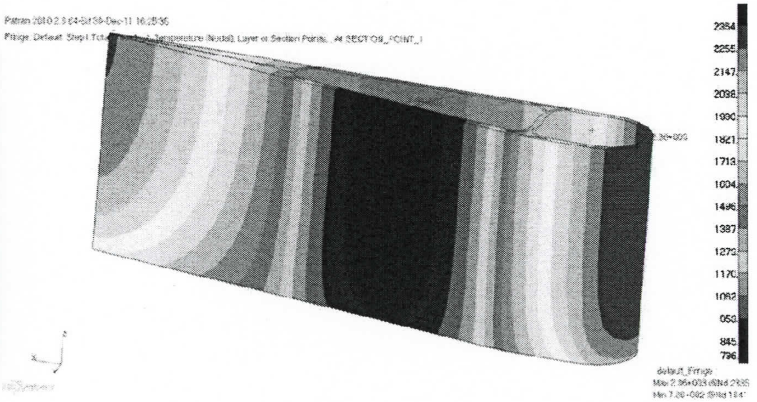
ERA CMC combustor liner and vane testing planned

High Pressure Burner Rig SiC/SiC CMC Vane Tests

- Completed initial tests of CMC turbine vane at 10 atm to validate FEM models
- EBC coated vanes will be tested to demonstrate current coating and CMC viability in burner rig simulated engine environments
- Study the impingement and film-cooled turbine vane and relevant failure modes
- Develop preliminary life prediction models


Vane after initial tests


Vane leading edge seen from viewport



Summary

- **Advanced high temperature SiC/SiC CMC environmental barrier coatings are being developed**
  - Emphasized thinner coating configurations with long-term stability and durability
  - Demonstrated higher temperature capability, improved environmental stability and coating thermal - mechanical stress and creep-rupture resistance
  - Focused on coating composition developments and architecture designs to minimize thermal stresses and improve durability to achieve 2700-3000°F capability, aiming at significantly improved thermal mechanical loading capability
  - Developed advanced coating processing methods and testing approaches related to turbine CMC combustors and vanes, establishing initial property database, degradation and lifing prediction models
  - Developed advanced combustor and turbine vane EBC technologies, and demonstrated the component and EBCs in relevant engine environments